Demonstration of Fischer-Tropsch Diesel Fuel in Cold Climates

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The main objective of this project was to study the potential use of ultra-clean Fischer-Tropsch (F-T) synthetic diesel fuel in cold-climate transit applications. Project activities included a winter transit bus demonstration of F-T fuel in Fairbanks, Alaska; a soil biodegradability analysis to determine the environmental effects of potential F-T fuel leaks; a feasibility study of the utilization of F-T fuels for hydrogen production in association with future transit fleet applications of reformer/fuel-cell power systems; and summarization of all of the transit-relevant emissions results to date for Syntroleum's F-T diesel fuel.

Major project findings include:

- F-T fuel can directly replace conventional (non-F-T) diesel fuel without modification to engines or significant changes in performance.
- Diesel fuel can be routinely stored, dispensed, and run successfully in buses at the cold temperatures.
- F-T fuel has a significantly higher rate of biodegradation than conventional diesel fuel.
- F-T fuel can reduce diesel exhaust emissions to levels significantly below those obtainable with even the lowest-emission conventional diesel fuels.
- F-T fuels could be utilized in hydrogen production in association with future transit fleet applications of reformer/fuel-cell power systems. However, on-board reformation is likely only an interim approach to a large-scale hydrogen fuel infrastructure.

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TABLE OF CONTENTS

TABLE OF FIGURES

ACRONYMS

APU	auxiliary power unit
BDL	below detection limit
BPD	barrel-per-day
C	Celsius
DDEC	Detroit Diesel Electronic Control
DOC	diesel oxidation catalyst
DOE	Department of Energy
DPX	diesel particulate filter
DRO	diesel-range organics
ERC	Energy Research Center
EPA	Environmental Protection Agency
FNSB	Fairbanks Northstar Borough
F-T	Fischer-Tropsch
FTA	Federal Transit Administration
FTP	federal test procedure
g	gram
GCMS	gas chromatography-mass spectrometry
HC	hydrocarbons
HCCI	homogeneous-charge compression-ignition
kg	kilogram
LDV	light-duty vehicle
MACS	Metropolitan Area Commuter System (Fairbanks)
MIT	Massachusetts Institute of Technology
mg	milligram
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PM	particulate matter
PEM	proton exchange membrane
R&D	research and development
Syntro	Syntroleum
TARDEC	Tank-Automotive Research, Development and Engineering Command
UAF	University of Alaska Fairbanks
ULSD1	ultra-low sulfur No. 1 diesel fuel
WVU	West Virginia University
WMATA	Washington Metropolitan Area Transit Authority

EXECUTIVE SUMMARY

The objective of this project was to study the potential use of ultra-clean Fischer-Tropsch (F-T) synthetic diesel fuel in cold-climate transit applications, as one of the perceived shortcomings of F-T fuels is that they may have poor low-temperature flow properties. Another goal of the project was to assess the relative environmental impact of F-T and conventional fuel leaks in terms of the biodegradability of both types of fuel.

The F-T fuels that were evaluated during the project were produced at Syntroleum Corporation's Tulsa, Oklahoma demonstration plant using the Fischer-Tropsch process to convert natural gas into liquid synthetic fuels. While natural gas was the feedstock for the fuel used in this project, the F-T process is also capable of converting coal and biomass into liquid synthetic fuels.

Major project activities included:
- A 24,000-mile, 5,000-gallon winter demonstration of Syntroleum arctic-grade F-T fuel in two urban transit buses in Fairbanks, Alaska.
- An extensive soil biodegradability analysis to determine the environmental effects of potential F-T fuel leaks.
- A feasibility study of the utilization of F-T fuels for hydrogen production in association with future transit fleet applications of reformer/fuel-cell power systems.
- Summarization of all of the transit-relevant emissions results to date for Syntroleum's F-T diesel fuel.

Major project findings:
- Arctic-grade Syntroleum diesel fuel can be routinely stored, dispensed, and run successfully in buses at the coldest temperatures likely to ever be encountered in any urban area in the U.S.
- F-T fuel can directly replace conventional diesel fuel without modification to engines or significant changes in performance.
- F-T fuel has a significantly higher rate of biodegradation than conventional diesel fuel, meaning that the F-T fuel is removed from the soil faster by bacterial action.
- Although most potential manufacturers of fuel cell-powered vehicles are now focusing on on-board storage of compressed hydrogen rather than on-board reformation of conventional liquid hydrocarbon fuels, F-T fuel's advantages, such as its lack of sulfur and aromatics, and its ability to be distributed by conventional national fuel distribution systems, may help make on-board reforming a viable interim step in bringing the advantages of fuel cell power systems to transit applications prior to the advent of the more expensive, higher-risk, and longer-term pure hydrogen economy.
- F-T fuel can reduce tailpipe diesel exhaust emissions to levels significantly below those obtainable with even the lowest-emission conventional diesel fuels.

F-T is a clean, low-emission fuel that does not require changes to vehicle engines or infrastructure, has a higher rate of biodegradability than conventional diesel fuel, performs well in cold weather, and has the potential for use in reformer/fuel-cell systems. Because it can be produced from domestically available feedstocks, F-T fuel also has the potential to help reduce U.S. dependence on foreign sources of oil. However, the price of F-T fuel is its major negative

factor. Although F-T can be produced from domestically available feedstocks, the costs of obtaining the most desirable feedstocks (such as natural gas), or of processing the cheaper but less desirable feedstocks (such as coal) would make it more expensive to the consumer than the imported petroleum products that currently fuel most transportation in the country. Until this price gap closes, or a more economical means of F-T production emerges, it is difficult to make an economic case for the widespread use of F-T fuel in transit applications. It is likely that F-T fuel will first be used extensively by the U.S. military, which is concerned more with energy security than immediate cost compared to imported petroleum products.

INTRODUCTION

The primary purpose of this FTA-sponsored project has been to study the potential for using ultra-clean Fischer-Tropsch (F-T) synthetic diesel fuel for transit applications in cold climates, with Alaska's climate representing the cold end of the spectrum. This project ran in parallel with a "warmer weather" FTA/ICRC demonstration of F-T fuel in Tulsa, Oklahoma. The F-T fuel that was evaluated in both Alaska and Oklahoma was produced at Syntroleum Corporation's plant in Tulsa, Oklahoma.

The report begins with a discussion of the plant and the F-T fuel it produced. The report then summarizes the project activities and results, including a summary of previously obtained bus-engine emission testing results that could be of value in estimating the emission-reduction potential of using F-T fuel in transit-bus applications.

FISCHER-TROPSCH FUEL BACKGROUND

The ultra-clean Fischer-Tropsch synthetic diesel fuel that was demonstrated during this project was produced at a pilot-plant that was built as part of a multi-year ICRC/Department of Energy (DOE) National Energy Technology Laboratory (NETL) project titled "Fischer-Tropsch (F-T) Production and Demonstration Program." The project included the design, construction, and operation of a 70 barrel-per-day (BPD) fuels-production demonstration plant by project-partners Syntroleum Corporation and Marathon Oil Corporation.

Fuel

A total of three types of F-T fuel were produced at Syntroleum's plant. The fuels contain virtually zero levels of sulfur, aromatics, and metals. They are virtually 100% composed of saturated hydrocarbon molecules, meaning that they contain the maximum possible amount of hydrogen. The molecules that make up these fuels differ in two primary characteristics:

1. In their distribution-range of carbon-number, with increasing contents of higher carbon numbers generally making the fuel "heavier," causing higher fuel viscosity, and;
2. In their degree of hydroisomerization, a manufacturing process that increases molecular chain-branching (as opposed to the straight-chain paraffin molecules that are contained in wax). The extent of hydroisomerization determines ability to resist "freezing" or the formation of a solid-structure at low temperatures. Note that hydroisomerization maintains hydrogen saturation despite the branching it causes in the structure of the fuel molecules.

The first of the fuels produced is Syntroleum's F-T version of No. 2 diesel fuel, which is called S-2. Syntroleum's menu of F-T fuel products also includes a "lighter" S-1 diesel fuel, generally corresponding to conventional No. 1 diesel fuel. However, for this particular project, the lighter S-1 fuel was also hydroisomerized to an even greater extent than usual for S-1 so that it would capable of being used successfully in arctic conditions. The third fuel produced at the plant was Syntroleum's F-T version of JP-8 jet-fuel, referred to as S-8. Although S-8 and arctic-grade S-1 must meet different specifications for different applications, these two fuels are actually very similar in practice.

The F-T fuels were produced using the Fischer-Tropsch process, which can convert natural gas (or other carbonaceous material) into liquid synthetic fuels. The process was invented in Germany in 1923, and was used in Germany during World War II, and during apartheid in the Republic of South Africa, when embargos were imposed. One of the main benefits of F-T fuel is that it can be produced from many different feedstocks, some of which the U.S. has in abundance.

F-T Fuel Feedstocks
Although F-T fuel could be made from any carbonaceous (carbon-containing), material, natural gas is by far the preferred feedstock from a technical standpoint. The primary reasons that natural gas is preferred are that:
1. In some technologies such as Syntroleum's, air (rather than oxygen) can be used in the natural-gas reformation process to produce syngas (a mixture of carbon monoxide and hydrogen), thus simplifying the overall plant.
2. Relatively little "clean-up" is required when syngas is produced by reformation of natural gas, and
3. Natural gas, which is mostly methane, produces H_2 (hydrogen) and CO (carbon monoxide) in the desired ratio of approximately 2:1.

Other carbonaceous materials, such as coal and biomass, are less desirable feedstocks for making F-T fuels because they:
1. Require relatively complex initial solid-material handling and processing before gasification,
2. Require the production and subsequent use of oxygen in the gasification process,
3. Require more complicated clean-up of the syngas, and
4. Produce a lower ratio of H_2 to CO that must be adjusted before F-T synthesis.

Chemistry
The conceptual chemistry involved in understanding the conversion of natural gas to synthetic hydrocarbon distillates can be summarized by two general chemical reactions.

The first general reaction is the partial combustion of natural gas to form a mixture of hydrogen and carbon monoxide, commonly known as syngas. A general reaction for the formation of syngas from methane is shown below.

$$\underset{Methane}{CH_4} + \underset{Air}{O_2 + N_2} + \underset{Steam}{H_2O} \xrightarrow{Catalyst} CO + \underset{Syngas}{H_2} + N_2 + \underset{Water}{H_2O}$$
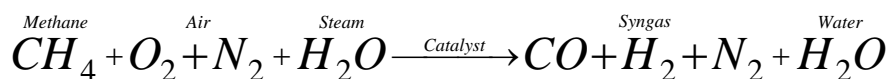
Syngas Reaction

The second general reaction is known as the Fischer-Tropsch (F-T) reaction and is shown below. The Fischer-Tropsch reaction recombines the carbon monoxide and hydrogen in syngas to form a variety of hydrocarbons of varying molecular weight and hydrocarbon chain length.

10

$$H_2 + CO + N_2 \xrightarrow{\text{Catalyst}} \overset{\text{Hydrocarbons}}{C_n H_{(2n+2)}} + \overset{\text{Nitrogen}}{N_2} + \overset{\text{Water}}{H_2 O}$$
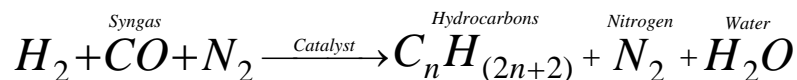
Fischer-Tropsch Reaction

Hydrocarbons formed can range from ethane to heavy waxes.   The raw Fischer-Tropsch product from the reactor contains what is typically described as a light Fischer-Tropsch syncrude (liquid at room temperature) and a heavy Fischer-Tropsch syncrude (solid at room temperature). Additional process equipment converts raw F-T material/product to synthetic versions of traditional hydrocarbon products such as naphtha, diesel, and jet fuel.

Advantages of F-T Fuel

1. No Additional Infrastructure Needed
The use of F-T fuel does not require any changes to vehicles or their engines. The general type of supporting infrastructure (fuel-tank, fuel-lines, pumps) and procedures required for fueling buses with F-T are no different than those required for conventional diesel fuel.

2. Potential Domestic Production
One of the main benefits of F-T fuel is that it can be produced from many different feedstocks, some of which the U.S. has in abundance, such as coal and biomass.   In the event of a major long-term interruption to U.S. oil imports, domestic production of F-T fuels from U.S. domestic resources will become a viable option, despite high costs compared to today's petroleum prices. This is why projects such as the NETL project described above and this FTA project are important to U.S. energy security—even if F-T fuel production technology is not currently cost-competitive with today's petroleum prices, these projects show that domestic production of F-T fuel is feasible and can be implemented when it becomes necessary, either in an emergency situation, or when increasing demand for petroleum causes prices rise enough to make F-T fuel production economical.

3. Reduced Tailpipe Emissions
The primary advantage of using F-T diesel fuel for transit bus applications is that an immediate reduction in diesel exhaust emissions can be obtained without making any changes to the buses or their engines. F-T fuel reduces both particulate and NOx emissions from diesel engines, but has relatively little effect on CO and hydrocarbon emissions. An analysis and summarization of emission data obtained by ICRC on bus engines operated back-to-back on F-T and conventional diesel fuels is provided at a later point in this report.

Obstacles to F-T Fuel Use

1. Feedstocks
While pipelined natural gas is technically an excellent feedstock for making F-T fuel, high demand and the costs associated with building, operating, and maintaining the pipeline make pipelined gas too expensive to be an economically viable feedstock for a commercial F-T fuels plant, at least at today's prices for petroleum products. Coal and biomass are far less expensive

and are more abundant domestically, but they are also more difficult (and thus require more expensive equipment) to process into F-T fuels.

2. High Cost Compared to Petroleum Products

Although the prices that U.S. consumers pay for petroleum products have risen recently, oil-derived fuels are still relatively "cheap" when one considers the costs, especially the capital cost, that would be associated with building and operating F-T fuel-production facilities, even if relatively cheap natural gas feedstock could be obtained. Even in remote areas such as rural Alaska, where small sources of low-cost gas natural gas might be available, and petroleum prices are currently the highest in the U.S., there is still too much of a price gap to make an economic case for small-scale F-T fuel production, especially when the additional financial risk associated with the initial commercial application of a new technology is also factored in.

In the absence of either government subsidies or extreme technological breakthroughs, very small F-T plants of only a few hundred barrels per day output of F-T diesel fuel almost certainly cannot compete economically with diesel fuel produced from petroleum until petroleum prices rise even higher. At September 2007 petroleum-price levels, even under the most seemingly "favorable" circumstances of high-cost diesel fuel and availability of potentially low-cost stranded natural gas, small-scale F-T does not yet appear to be sufficiently attractive as a high-profit, low-risk business venture.

FTA ALASKA PROJECT

As Alaska may well contain most of the country's stranded natural gas and consistently faces the highest prices in the country for conventional petroleum products such as diesel fuel in remote areas, it is likely to eventually be the first location in the U.S. where small-scale local production of F-T fuels for local use will be able to compete economically with conventionally refined petroleum-derived fuels. This Alaska-centered project focused on running and storing F-T fuel in cold climates, both major issues. To study the operation of vehicles running on F-T fuel in cold climates, ICRC and the University of Alaska-Fairbanks (UAF) conducted a transit bus demonstration in Fairbanks, Alaska during the winter months. The University also conducted soil biodegradability analysis to determine the environmental effects of potential fuel leaks.

Running F-T Fuel in Cold Climates
One of the perceived shortcomings of F-T fuels is that such fuels may have poor low-temperature flow properties. If this were true, it might indicate that F-T fuels would not be particularly desirable for use in cold-weather conditions such as those faced much of the year in Alaska. This perceived deficiency apparently stems from the fact that long-chain normal paraffins (i.e. wax) make up a significant portion of the raw syncrude product from Fischer-Tropsch synthesis. However, the production of finished F-T fuels always requires at least some level of upgrading of the syncrude.

One step in the F-T syncrude upgrading is hydrocracking, which reduces the chain length of the normal paraffin molecules to the desired range for the finished product being produced, such as diesel fuel or jet fuel. Hydrocracking improves low-temperature flow properties to some extent simply by reducing molecular chain lengths. However, hydroisomerization is almost always required to make finished fuels that will meet the low-temperature flow specifications for the climate conditions in which they will be used. [1]

The Fairbanks, Alaska, transit bus demonstration was an ideal opportunity to demonstrate that the highly isomerized arctic-grade version of the Syntroleum F-T diesel fuel is capable of performing well in the environment that is the coldest of virtually any U.S. urban area.

Storing F-T Fuel in Cold Climates
Diesel fuel storage tanks almost always have some water in the bottom. Some of the water may come in with each new shipment of fuel. But even if all shipments are water-free, water will accumulate over time from normal "breathing" of the tank. The amount of atmospheric air in the head-space of the tank above the fuel increases as the fuel is pumped out of the tank and as the ambient temperature drops. Incoming atmospheric air always has some level of humidity. Over time, temperatures change, and some water will condense out of the air in the tank and find its

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[1] Hydroisomerization causes branching of the molecular chains while retaining hydrogen saturation of the molecules. The severity of hydroisomerization applied, or the extent to which the branching-structure of the F-T fuel molecules is increased by "deeper" hydroisomerization, determines the additional improvement in low-temperature flow properties of the F-T fuel that will be obtained. For example, production of jet-fuel or arctic-grade diesel fuel requires high-severity hydroisomerization. However, hydroisomerization severity is limited to the level that is actually required for a given application, because this process, like most others, has a cost associated with increasing severity. Increased hydroisomerization severity increases the amount of hydrogen consumed during product upgrading and reduces the product yield from a given amount of syncrude.

way to the bottom of the tank, where it will remain unless significant effort is put into removing it on a continuing basis.

In Alaska's climate, the water in fuel tanks is virtually certain to freeze at times, even in the legacy underground-tank applications. These freezing and thawing cycles take their toll on all materials and are likely to eventually compromise the integrity of the tank, potentially leading to leaks. Generally speaking, fuel leaks in a cold climate are even worse than leaks in a more moderate climate, because the natural bacterial processes that eventually "degrade" the fuel, and thus essentially eliminate it and its bad effects from the environment, are likely to occur more slowly in a cold climate. Therefore, the characteristic biodegradability of a particular diesel fuel that could be used in Alaska, especially in the coldest climates, is a significant environmental issue. The University of Alaska Fairbanks compared the biodegradability of conventional and F-T diesel fuels by analyzing their impact on ground soil under various conditions.

Besides the major cold-weather issues, the project also included a study of the utilization of F-T fuels for hydrogen production in association with future transit fleet applications for reformer/fuel-cell power systems.

The final goal of the project was to provide a summary of all of the transit-relevant emissions results to date for Syntroleum's ultra-clean F-T diesel fuel. Next to cost, the potential for reducing emissions may be the most important aspect of a transit system's decision whether or not to use a particular fuel. This single point of reference is intended to assist decision-makers in evaluating the potential use of F-T fuels in their fleets.

A. Cold Climate Bus Demonstration

The main objective of the Fairbanks transit bus demonstration was to show that highly isomerized arctic-grade F-T diesel fuel can be routinely stored, dispensed, and run successfully in buses at the coldest temperatures likely to ever be encountered in any urban area in the U.S. Data collected included transit personnel observations, fuel usage/fuel economy, and a "quick-and-dirty" check of on-road gaseous emissions using a portable analyzer on-board a bus operating on both F-T and conventional No. 2 diesel fuels. Ultra-low sulfur diesel (ULSD) was not yet required for on-road use when this demonstration took place in 2005.

Demonstration Overview
The cold-weather phase of demonstration ran from mid-December 2004 to late April 2005 on an urban transit route in Fairbanks, Alaska, with temperatures ranging from below -40°F up to about +50°F. The two buses running exclusively on F-T fuel covered a total of 23,720 miles during the cold-weather phase, and consumed 5,451 gallons of arctic grade F-T fuel. When the weather warmed up in late April 2005, the same buses continued to use the arctic grade F-T fuel for some fill-ups, but No. 2 diesel fuel use was interspersed because the transit agency had concerns about continuing the exclusive use of the very light arctic grade fuel at (what they considered to be) very warm temperatures. The concern was apparently based upon the perception by the agency that the lubricity of arctic grade F-T fuel, if used exclusively, might not be sufficient to protect the engine's fuel injection system at warm temperatures. However, several previous evaluations of the lubricity of the Syntroleum F-T fuel during the NETL Project have shown that the commercially proven lubricity additive treatment applied to all Syntroleum diesel fuels, including arctic-grade, is fully capable of protecting diesel fuel systems under the full range of real-world operating conditions. With the exception of changing fuel filters and draining tanks to segregate the F-T fuel from the No. 2 diesel, operations were conducted as though the F-T was the agency's "regular" winter fuel.

Photo 1. Dispensing tank at the Fairbanks Northtstar Borough Department of Transportation

Fuel Storage and Dispensing
The 6,970 total gallons of F-T fuel that were demonstrated were stored in an 8,000-gallon, dual-walled and fire-rated bulk dispensing tank. Fortunately, contamination was not an issue, as the tank had previously contained only F-T fuel, as part of the diesel-generator testing portion of the NETL project described above. To prepare for operation on F-T fuel, FNSB maintenance personnel drained the bus fuel tanks and changed the fuel filters on the demonstration buses. FNSB maintenance personnel filled the tanks of the buses at the end of each day so that buses could begin operations the next morning with full tanks. Fuel dispensing was carefully tracked and recorded. Since the F-T fuel for the two demonstration buses was stored in its own separate tank and clearly segregated from the conventional fueling area, misfueling was effectively prevented.

Demonstration Buses
The two buses used to demonstrate the F-T fuel are very similar. Both are 1994 Phantom models, manufactured by the Gillig Corporation. The engines in both buses are turbocharged Detroit Diesel Series 50 engines, incorporating the Detroit Diesel Electronic Control (DDEC) electronic fuel injection system. Both buses were nearing the end of their service life at the time of the demonstration, with approximately 500,000 miles on each of their odometers at the start. The buses operated normally on their scheduled urban transit routes while using the F-T fuel. After April 22, 2005, the two buses used for the demonstration project operated on both No 2. diesel and F-T fuel.

Driver Observations
The bus drivers were generally satisfied with the F-T fuel. The only change that the bus drivers and mechanic observed when using the F-T fuel turned out to be attributable to other factors. After the buses began running on the F-T fuel, the bus drivers reported operational symptoms that they attributed to the F-T fuel, specifically that the buses operating on it did not seem to have the same amount of power as the buses running on No. 2 diesel fuel. The FNSB mechanic corroborated the drivers' perceptions; however, after switching the demonstration buses back to conventional fuel, the mechanic noticed no change in operation characteristics. There was also no noticeable change in operation during an end-of-season test when operation was switched to F-T from conventional fuel for a single day. Since the specific buses used for the demonstration seemed to lack power on both No. 2 diesel and F-T fuel, FNSB personnel concluded that the loss of power could be explained by the fact that the engines in the buses were nearing the end of their useful lives of approximately 500,000 miles.

Data Collection and Interpretation

1. Fuel Economy
Fuel economy was reported in two ways. First, FNSB personnel compared the two buses running solely on F-T; FNSB then compared the two F-T-fueled buses with one run on No. 2 diesel.

The average fuel economy achieved on the two buses run on F-T fuel from the beginning of the demonstration through April 22, 2005 was 4.4 miles per gallon for bus X941, and 4.3 miles per gallon for bus X942.

Day-to-day differences in ambient outdoor temperature can significantly affect the efficiency of an internal combustion engine. Even though average temperatures during the winter months of testing were -5°F, temperature variations of 10°F within a few hours and variations of 40°F within a few days were not uncommon.

The relationship between fuel consumption and ambient temperatures is more easily observed when the data is presented in a graphical format. Figure 1 displays fuel economy using a running average of seven fill-ups to reduce the effect of variations of filling techniques by different individuals. To illustrate the relationship between temperatures and fuel consumption, hourly ambient outdoor temperatures are also plotted.

The primary conclusion to be drawn from Figure 1 is that when ambient temperatures were consistently below -20°F, the fuel economy of both buses dropped below four miles per gallon. For less severe temperatures, fuel economy was virtually always above four miles per gallon, and approached five miles per gallon when ambient temperatures were consistently above +20°F.

Figure 1. Fairbanks Demonstration Fuel Economy and Ambient Temperatures vs. Time
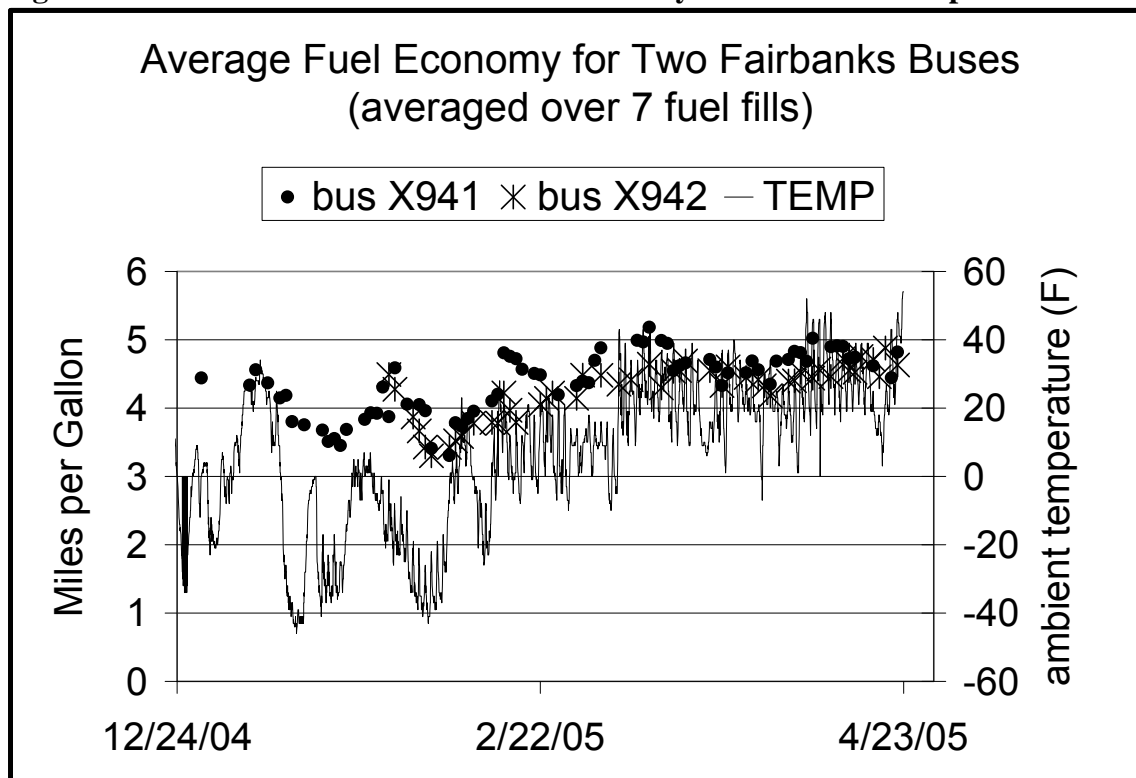
Table 1 compares the fuel economy between F-T and No. 2 diesel for three of the buses operating during three months of the demonstration. This time period was chosen to provide as much comparison data as possible for a common time period for the three buses and the two fuels. The density (pounds per gallon) of No. 2 petroleum-derived diesel fuel is greater than that of hydrogen-saturated F-T diesel fuel. Therefore, fuel economy in miles per gallon is expected to be greater with conventional diesel fuel than with F-T diesel.

Table 1. Fairbanks Demonstration Syntroleum F-T and No. 2 Diesel Economy Comparison

	Dates of Operation	Fuel use during time period (gallons)	Distance Operated (miles)	Fuel type	Fuel Economy (miles per gallon)
bus X941	2/2/05 – 4/29/05	2316	10271	F-T	4.4
bus X942	2/2/05 – 4/29/05	2008	7988	F-T	4.0
bus X943	2/2/05 – 4/29/05	2202	10693	No. 2	4.9

2. Emissions

Near the end of the demonstration on March 29, 2006, UAF researchers performed an emissions check on bus X941 of the Fairbanks Northstar Borough's Metropolitan Area Commuter System. Photo 2 shows bus X941 on the cool, clear afternoon just prior to the emissions sampling.

Photo 2. Fairbanks Northstar Borough Metropolitan Area Commuter System bus X941

This comparison did employ back-to-back runs of the same bus on the two fuels. However, the other five items listed in the Appendix as requisites for meaningful comparisons of fuel-property effects on engine emissions could not be fully attained during these on-road checks of gaseous emissions using a portable analyzer. Nonetheless, this emissions check was a valuable exercise for the information it ultimately provided on the condition of the bus engine, even if it was not likely to be able to quantify precisely the relatively small differences in engine emission levels attributable to differences in fuel properties.

The bus operated on conventional No. 2 diesel fuel for the first emissions check. Upon the bus' return to the FNSB facility, the mechanic drained the No. 2 diesel from the fuel tank and changed fuel filters. The mechanic then filled the fuel tank in the bus with F-T fuel for the next test. For each test, the operator drove the bus until it reached normal operating temperatures. During these tests, the ambient temperature was approximately 20°F, with a light breeze of approximately five mph from the north.

A NOVA Model 7465 DNN exhaust analyzer was used to check the exhaust emissions. The primary intended use for this device is apparently to "check" emissions and thus quickly identify those engines (in a large fleet perhaps) that have such unusually high emissions that "engine problems" may be starting to occur, even if the overall performance of the engine still seems to be acceptable.

Photo 3. Emissions Analyzer Probe in Exhaust of Bus X941

To allow for real-time sampling during on-road operation, the analyzer sampled exhaust gases through a probe fixed to the exhaust stack, with the sample line led through a roof hatch to the equipment operators in the coach. Photo 3 shows the physical placement of the exhaust sampling probe in the exhaust stack of bus X941. For each fuel, the bus operated

under steady state load conditions of approximately 40 to 50 mph while the emissions analyzer sampled exhaust gases. During the period when the bus was under load, the analyzer recorded two samples two minutes apart. At the end of each run, the bus idled, allowing the analyzer to sample exhaust gases under no-load conditions. This resulted in three exhaust emissions samples for operation with each fuel, two samples under load and one idle sample. Photo 4 shows operation of the NOVA portable emissions analyzer while the bus operated on borough roads.

Photo 4. Operation of NOVA emissions analyzer in bus X941

Table 2 presents the results of the six emissions samples taken. The emissions monitor provides readings for both Nitric Oxide (NO) and Nitrogen Dioxide (NO_2). The literature usually refers to oxides of nitrogen, NO_x, a term that includes both NO and NO_2.

Considering the relatively crude methods employed, the emission-check results are quite consistent from run to run. However, it would be a "stretch" to attempt to attribute the differences in emission levels to fuel properties. For example, this analyzer apparently has relatively low sensitivities to both CO and hydrocarbons. Consistent with the idea of using this portable analyzer as a screening tool for potential early-stage engine problems, engines that are operating properly should have low levels of both CO and hydrocarbons when measured on these scales. However, the early stages of the common diesel engine problem of fuel-injector nozzle-leakage, for example, would produce much higher levels of CO and hydrocarbons that this analyzer would apparently be able to detect.

Table 2. Fairbanks Demonstration NOVA Analyzer Emissions Results

	Sample 1 No. 2 diesel under load at 45 mph	Sample 2 No. 2 diesel under load at 45 mph	Sample 3 No. 2 diesel idle	Sample 4 Syntroleum S-1 F-T under load at 45 mph	Sample 5 Syntroleum S-1 F-T under load at 45 mph	Sample 6 Syntroleum S-1 F-T idle
O_2 (%)	14.9	14.0	18.5	15.6	15.5	18.3
CO (%)	0.01	0.00	0.00	0.00	0.01	0.00
CO_2 (%)	4.4	5.0	2.0	5.1	4.7	1.9
HC (ppm)	6	9	5	4	6	5
NO (ppm)	300	315	353	193	359	242
NO_2 (ppm)	48	45	53	32	53	66

The results from a Series 50 Detroit Diesel engine, virtually identical to the engines in the demonstration buses, operated as a stationary power plant at the University of Alaska Fairbanks Energy Research Center (ERC) as part of the NETL project referred to previously, are consistent with the results of the emissions sampling with the portable exhaust analyzer. On the basis of simple averaging of all values for a given pollutant on each fuel, the bus exhaust contained less NOx (NO_2 and NO) and unburned hydrocarbons (HC) when operating with F-T fuel than with No. 2 diesel. The emissions tests at the UAF ERC indicated that operation on the S-2 F-T fuel resulted in 18% lower unburned hydrocarbons than when operating on No. 2 conventional diesel, and that NOx emissions decreased by 12% when using the F-T fuel (Telang, 2005). The test at the UAF ERC on the Series 50 Detroit Diesel ran for 2,000 hours and the emissions test followed Environmental Protection Agency (EPA) protocols for stationary sources.

Caution Regarding Fuel Changes
The purpose of this demonstration was to show that the use of synthetic F-T fuel could be seamlessly integrated into operations of a transit system in the Arctic, and it was successful. In contrast, not all fuel tests are so uneventful, and illustrate why transit managers are often cautious of using unfamiliar fuels. One such test was UAF's 2,000-hour test of fish-oil based biodiesel fuel (a potentially environmentally friendly alternative to petroleum-derived diesel fuel for some applications in Alaska) on a similar Detroit Diesel Series 50 engine.

The test fish-oil biodiesel was stored in multiple bulk containers, and exhibited different properties depending on which container provided fuel for a given test. The engine failed within seconds of introducing a fuel exposed to the atmosphere for a longer period than other batches of fuel, and did not restart even after introducing other fuel.

UAF used Detroit Diesel Electronic Controls (DDEC) software tools to try to discern the reason for failure to start. The tools indicated an injector malfunction as the possible reason for failure. Logged data from the data acquisition system monitoring the engine was also reviewed carefully.

This data indicated adequate fuel pressures in the engine fuel system. The behavior of the engine during restart attempts suggested that no fuel was being delivered to the cylinders. (Sastry 2005).

This symptom called for fuel injector removal and inspection. A relief poppet valve in the injector body remained in the open position, preventing fuel from being delivered out of the injector nozzle. In addition to the stuck valve, carbon-like deposits fouled the injector nozzle. It appeared that a varnish on critical injector components resulted in the failure.

After this event, lab personnel performed an experiment to approximate the fuel environment in an injector. The experiment resulted in varnish formations from the biodiesel, while the F-T fuel remained varnish-free.

Fairbanks Demonstration Conclusion
The most significant conclusion to the demonstration is that FNSB staff observed no fuel-related problems, and no maintenance issues were attributable to the use of F-T over the 2,000 hour, 30,000 mile test. The operation demonstrated that F-T fuel can directly replace conventional diesel fuel without modification to engines or significant changes in performance, since switching between F-T and No. 2 diesel fuel remained uneventful. The use of F-T fuel did not have an adverse effect on emissions.

Cold weather characteristics are an important consideration in any Arctic endeavor and the F-T fuel performed well during cold weather operations in temperatures as low as -40 F.

While this demonstration can be considered a success, not all demonstrations are as smooth. The comparison between the results of the FNSB transit test and the biodiesel testing at UAF illustrates that transit operations managers may be justifiably conservative when considering using different types of fuel in their systems. They must weigh the benefits of new fuels versus the consequences of problems such as reduced reliability or increased capital and maintenance expenditures.

B. Biodegradability Testing

The University of Alaska Fairbanks evaluated the F-T fuel by comparing it to conventional No. 2 diesel and fish biodiesel, a cheaply available waste product from Alaskan fish processing plants. Over a period of several months, UAF conducted microcosm experiments to investigate the effect of temperature (6°C vs. 20°C), moisture content (2%-12%), and nitrogen-fertilizer nutrient addition (0 vs. 300 mg N/kg soil) on the biodegradation of the different fuels in two types of soil (sand vs. gravel). Biodegradation was characterized by measuring CO_2 production by naturally occurring microbes during the course of the experiment and by gas chromatography-mass spectrometry (GCMS) analysis of diesel-range hydrocarbons remaining in the soil at the end of the experiment. Because CO_2 is the main product in aerobic breakdown of organic molecules, CO_2 production indicates the level of microbial activity. One set of experiments examined the adaptation period (lag times) of the microorganisms to the different types of fuels under optimum conditions.

For each experiment, 1kg of soil (sand or gravel) was placed in an airtight 2.5-liter container. Quantified amounts of the chosen contaminant (i.e. the fuel to be evaluated) were added to the previously uncontaminated soil. Additionally, a small amount of previously contaminated soil was added to provide an inoculum of microbes.

Data was collected over different time periods. F-T and No. 2 diesel fuel were investigated for five months while fish biodiesel was added later to the experiment.

Results
F-T fuel and No. 2 diesel showed similar trends for hydrocarbon removal from the soil by microbial respiration. However, in almost every experiment, the F-T fuel had a significantly higher rate of biodegradation than No. 2 diesel fuel, meaning that the F-T fuel was being removed from the soil faster by bacterial action. In the extended five-month experiment at 20°C, a 36% higher cumulative amount of CO_2 was produced for the F-T fuel compared to the diesel and an approximately 60% higher amount at 6°C (Figure 2). The results indicate that F-T fuel was biodegraded faster than conventional diesel fuel because F-T was favored over diesel fuel by the naturally occurring microorganisms that are already present in the soil.

Temperature
Temperature mainly influenced the adaptation times, or the times required for the bacteria to adapt to the fuel and begin degrading the fuel at a high rate, as indicated by the rate of CO_2 production. Although the bioremediation process started much earlier for higher temperatures compared to lower ones, microbes adjusted to the lower temperature and degraded the hydrocarbons to a significant extent. After a period of three months, the cumulative CO_2 production at 6°C reached about 2/3 of that observed for 20°C. After the first month, during which respiration rates (i.e. the slopes of curves in Figure 2) at 20°C peaked and then declined, actual rates at 6°C were even slightly higher than those for 20°C (Figure 2).
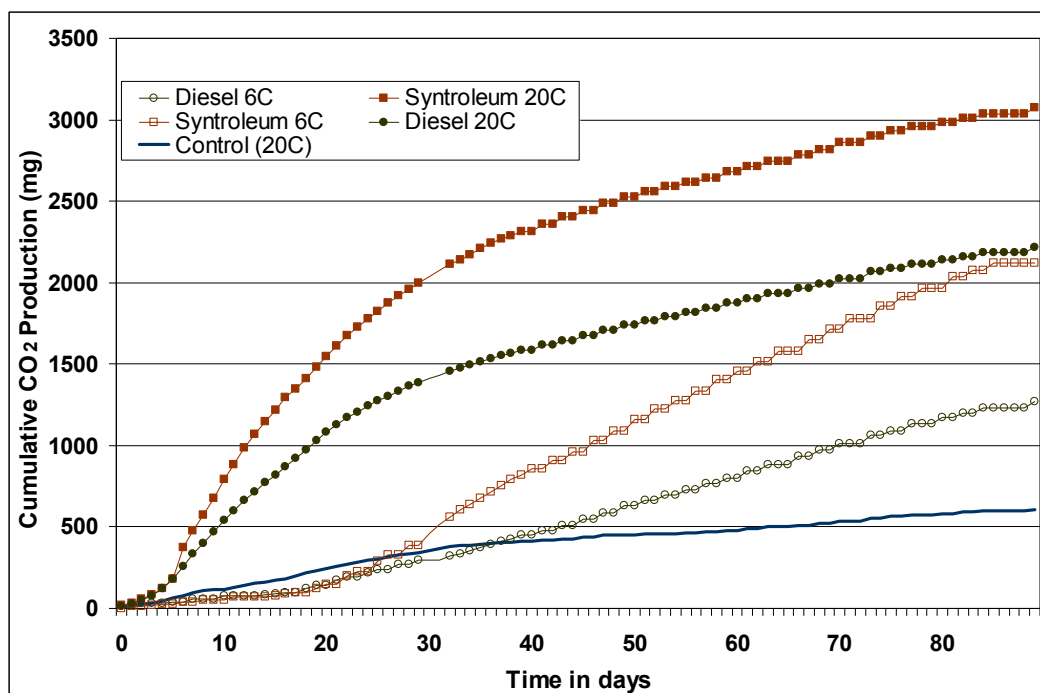
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Figure 2. Effect of Temperature on Respiration of Syntroleum F-T v. Diesel, Reported as Cumulative Amount of CO_2 (mg). Conditions: 2g/kg of fuel, 300 mg N/kg, sand. The control line represents soil without fuel and 300 mg N/kg.

Nutrient Addition and Moisture Content

In nutrient deficient soils such as those used in this experiment, the addition of nitrogen and phosphate was necessary to achieve high degradation results. Fertilizer addition increased the amount of CO_2 produced by a factor 2.6 in the case of the F-T fuel, compared to the soil with a very low natural nutrient content. Moisture content proved to be a negligible factor between 2% and 12% as volumetric water content. Intensive agitation was shown to be irrelevant as a biodegradation enhancement factor, indicating that mass transfer in the bulk soil did not appear to be a rate limiting factor.

Time

In order to determine how much carbon actually remained in the soil as a function of time, the soil was analyzed by GCMS after different time periods. Figure 3 shows that during the first week, the CO_2 production is minimal, and the contamination in the soil is very high. As time progresses, the amount of carbon dioxide produced increases strongly and the amount of contamination remaining in the soil (determined by GCMS) decreases significantly. The high percentage of "other" carbon can be explained by the relatively short duration of the experiment where bacterially-driven mineralization (or bio-degradation of the fuel) was less complete. The disappearance of the carbon from soil was not always directly related to the CO_2 produced, because some of the total carbon originally in the fuel accumulated into biomass, evaporated to the atmosphere, or was incompletely degraded. In general, only about half of the initially added carbon was recovered as diesel-range organics (DRO) in the soil or as CO_2 in the gas phase.
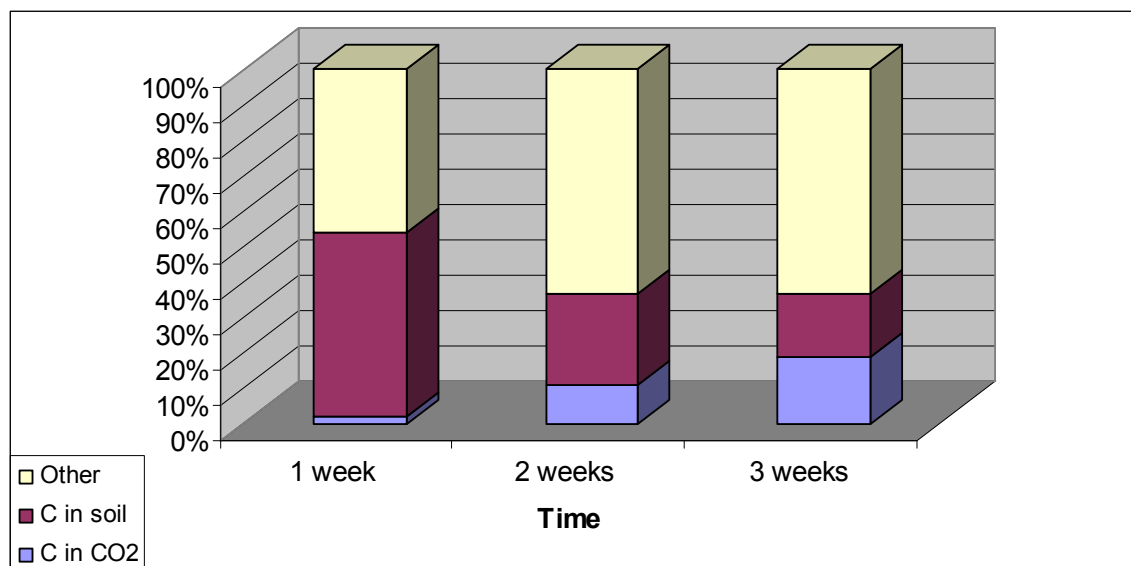
Figure 3. **Carbon Mass Balance for Syntroleum F-T After Different Time Periods.** Conditions: 20°C, 2g/kg fuel (Syntroleum), 300 mg N/kg, sand and <12% volumetric water content.

The percentage of hydrocarbon mineralized by bacterial action within a six-week period was highest for Syntroleum F-T with 29%, followed by fish biodiesel with 24% and diesel with 19%. The highest microbial mineralization, about 90%, was achieved while investigating the F-T fuel over the course of four months.

When each sample was inoculated with a population that was already adapted to the fuel type that was added, degradation of the F-T fuel started within less than a day and the lag phase (where microbial activity is slow) was less than a week (Figure 4). During the first two weeks, fish biodiesel showed little biological action, but by the end of week three the CO_2 production becomes very significant, which appeared linked to fungal growth, and eventually similar total CO_2 production was achieved for No. 2 diesel. The highest weekly rates occurred between weeks two and three, when the F-T had three times higher cumulative CO_2 production than the No. 2 diesel fuel. Since samples contaminated with F-T fuel were inoculated with soil from the prior F-T degradation experiment, an optimally adapted bacterial population was already initially present. By the end of a three week period, 20% of the F-T fuel was already microbially mineralized under optimal conditions, which was 1.5 times higher than for No. 2 diesel (13.5%).
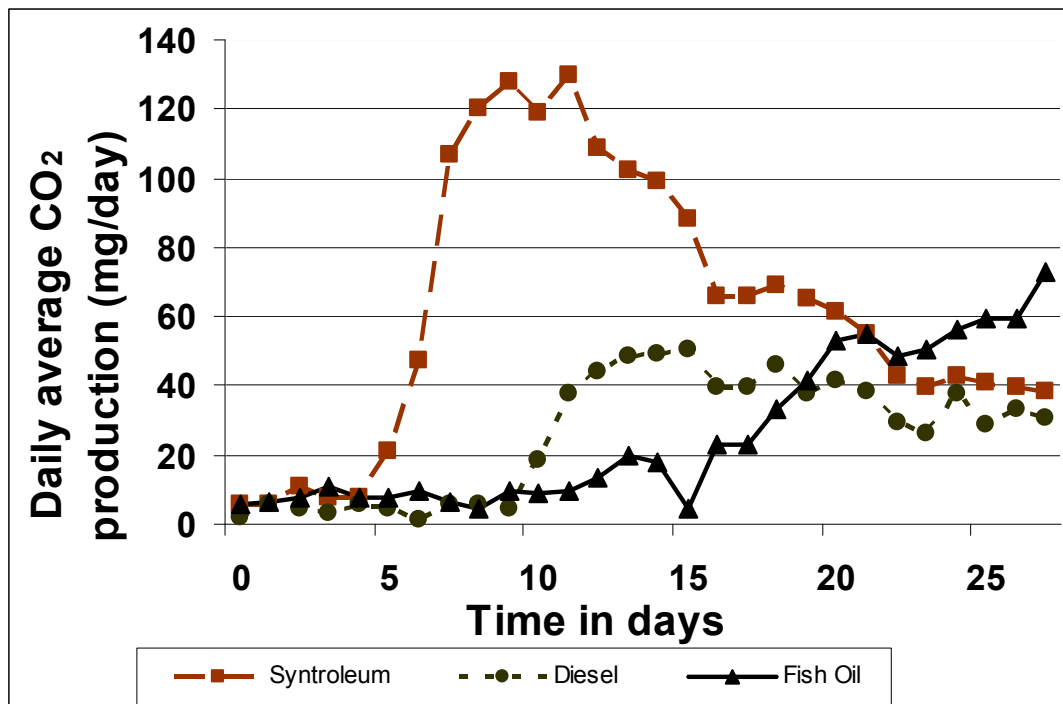
Figure 4. Respiration Rates for the Three Types of Fuel During Different Microbial Growth Phases. Conditions: 20°C, 2 g/kg of F-T, No. 2 diesel and fish biodiesel, 300 mg N/kg, sand and <12% volumetric water content.

Biodegradability Conclusion

Experimental data generated over a period of several months show that the two main types of fuel, F-T and No. 2 diesel, have similar biodegradation profiles. However, in almost every experiment, the F-T fuel had a significantly higher rate of biodegradation than No. 2 diesel fuel, meaning that the F-T fuel was being removed from the soil faster by bacterial action. Longer lag phases were observed for fish biodiesel, meaning that more time was required for the soil bacteria to adapt to the fuel and begin degrading the fuel at a high rate, as indicated by the rate of CO_2 production. The moisture content in sand proved to be only a minor factor. Although the bioremediation process started much earlier for higher temperatures compared to lower ones, microbes adjusted to the lower temperature and degraded the hydrocarbons to a significant extent. After a period of three months, the cumulative CO_2 production at 6°C reached about 2/3 of that observed for 20°C. After the first month, during which respiration rates at 20°C peaked and then declined, actual rates at 6°C were even slightly higher than those for 20°C.

C. F-T Emissions Compilation

Diesel-engine exhaust emissions on F-T fuel and conventional diesel fuels were measured during the NETL project described in the introduction section of this report. One of the goals of this FTA project is to provide a summary of the emissions testing that had been completed on the Syntroleum F-T fuel thus far.

ICRC collected emissions data during the two major bus demonstrations that were part of the NETL project: an urban transit-bus demonstration at the Washington Metropolitan Area Transit Authority (WMATA) in Washington, DC, and in wilderness tour buses at Denali National Park in Denali, Alaska. Emissions data was also collected from dynamometer emissions tests that were conducted on bus engines identical to those used in the WMATA and Denali demonstrations.

Back-to-Back Emission Data for F-T and Conventional Fuels
Measurement of the difference in diesel engine exhaust emissions (which can be attributable to as subtle an influence as differences in fuel properties) requires an excellent degree of control over all other potential variables, as described in appendix A. This demands, in addition to excellent control of operating conditions, exhaust sampling, and instrument calibration, that back-to-back emission testing on the test-fuels to be compared to minimize engine and vehicle variations. Figures 5 and 6 show, respectively, particulate matter (PM) and NOx emissions from a WMATA bus operated back-to-back on ultra-low sulfur No. 1 diesel fuel (ULSD1) and on Syntroleum F-T diesel fuel as measured by West Virginia University (WVU). Another aspect of this back-to-back comparison is the exhaust aftertreatment equipment installed on the bus. (Wayne, et. al. 2006)

Figure 5. PM emissions from a single WMATA bus operated on ULSD1 and on Syntroleum S-2 F-T diesel fuels, with two different exhaust-aftertreatment configurations; the original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX)

Figure 5 shows that Syntroleum F-T diesel fuel reduces particulate matter emissions for the stock-DOC bus by more than 30% compared to the lowest emission conventional (non-F-T) diesel fuel, ULSD1. The retrofitted catalyzed diesel particulate filter greatly reduces PM emissions for both fuels, and indicates that the F-T diesel fuel is, at the very least, compatible with particulate filter technology. In fact, the lower engine-out PM emission rate obtained with F-T fuel means that the DPX filter needs regeneration, or burn-off of accumulated particulate matter, is required less often. This slower accumulation of particulate matter in the diesel particulate filter was indeed verified by laboratory tests conducted at the Massachusetts Institute of Technology (MIT) which is expected to result in a longer service-life for the diesel particulate filter. (Wong, 2006).
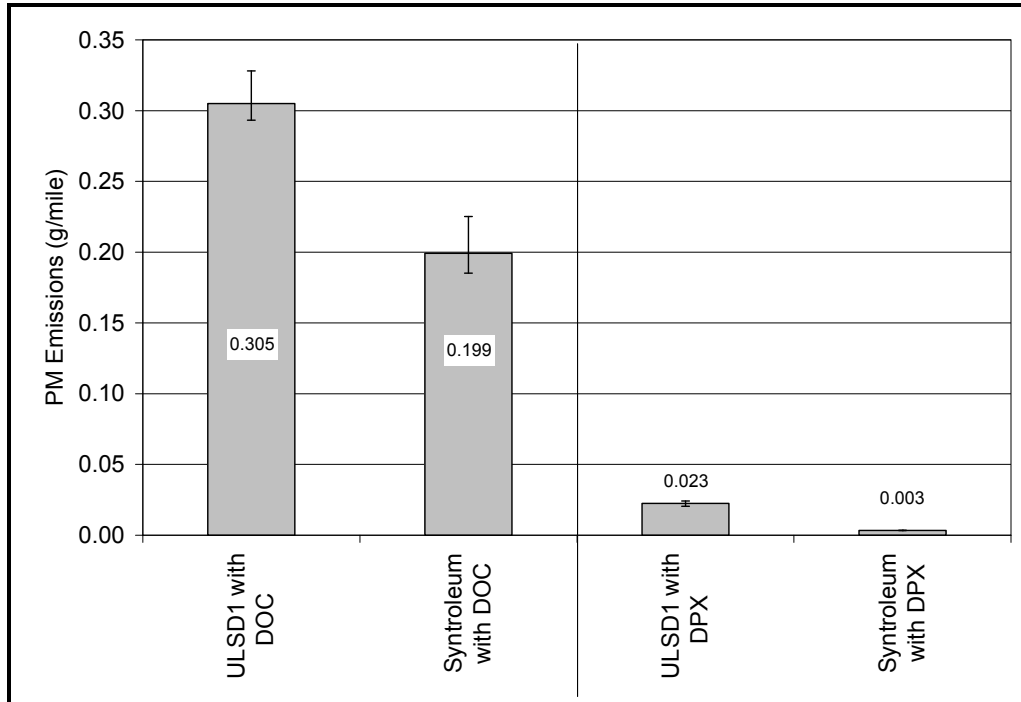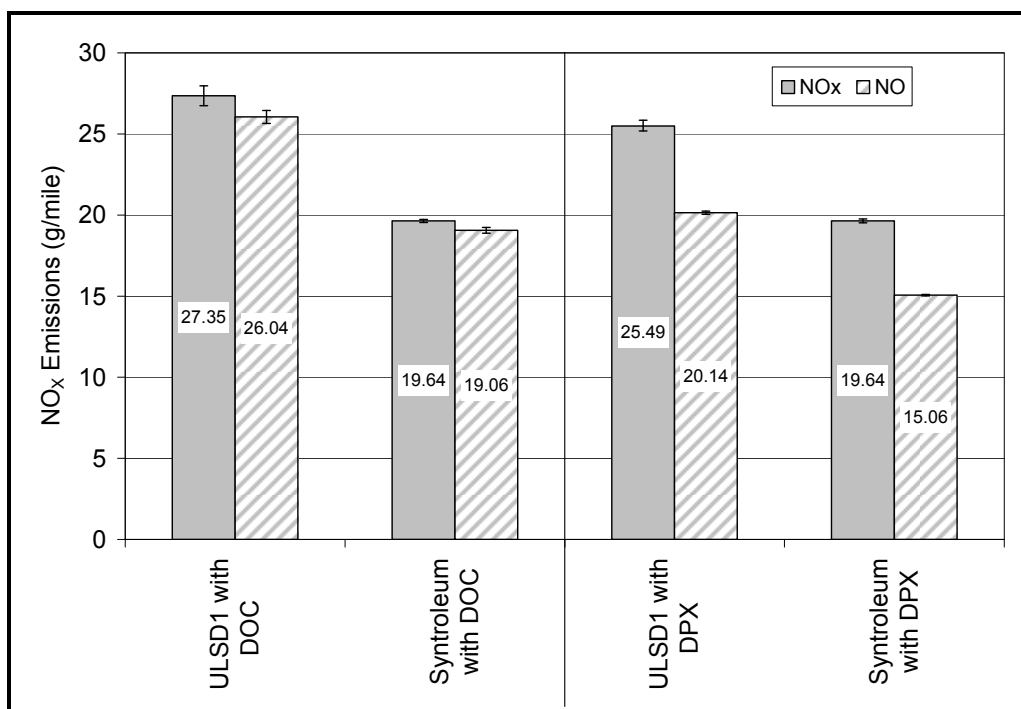
Figure 6. Oxides of Nitrogen (NOx and NO) emissions from a single WMATA bus operated on ULSD1 and on Syntroleum S-2 F-T diesel fuels, with two different exhaust-aftertreatment configurations; the original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX)

Figure 6 shows that Syntroleum F-T diesel fuel reduces NOx emissions for the stock-DOC bus by more than 20% compared to the lowest emission conventional diesel fuel, ULSD1. Figure 6 also shows that the diesel particulate filter has virtually no effect on NOx emissions for either fuel, as expected. However, the catalyzed diesel particulate filter does appear to oxidize some of the NO originally in the exhaust to NO_2. This reduces the amount of NO measured in the exhaust, but has no significant effect on total NOx emissions.

Particulate and NOx emissions are usually considered together because of the well- known particulate/NOx emission tradeoff. Many approaches that could reduce emissions of one of these species produce a corresponding increase in the other.

Figure 7 shows that CO and HC emissions are about the same for F-T and ULSD1 fuels for the stock-DOC vehicle configuration. However, Figure 7 also shows that the diesel particulate filter (DPX) is far more effective in reducing CO and HC emissions than the DOC for both fuels.
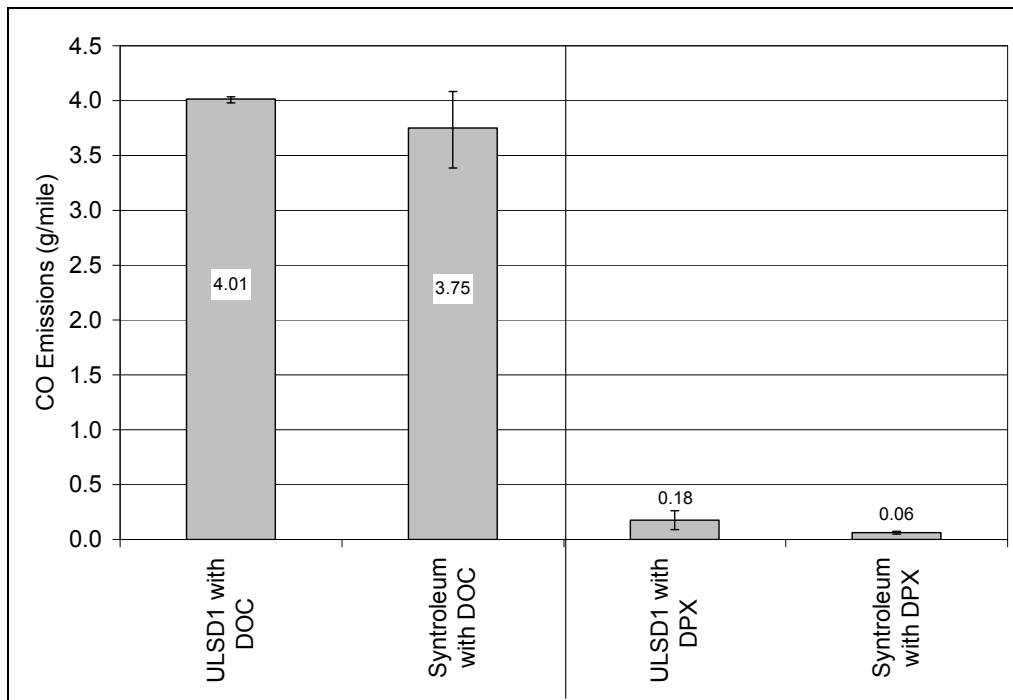

Figure 7. Hydrocarbon (HC) emissions from a single WMATA bus operated on Ultra-Low Sulfur No. 1 Diesel (ULSD1) and on Syntroleum S-2 F-T diesel fuels, with two different exhaust aftertreatment configurations; the original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX).

Table 3 is a summary of back-to-back particulate and NOx emission measurement results comparing Syntroleum S-2 F-T diesel fuel to the same conventional low-emission fuel, ULSD1, for three separate data sets. The first column of results summarizes the results in Figures 5 and 6 for the single WMATA bus in its stock configuration with the diesel oxidation catalyst. The second column of results gives the average reductions in PM and NOx for three similar WMATA buses measured under the same conditions at a later time.

Back-to-Back Data Source	1 WMATA Bus (Figures 1 thru 4)	3 Bus Average (WMATA buses)	Dynamometer Emission Test
Engine	DDC Series 50	DDC Series 50	Caterpillar C-7
Exhaust Aftertreatment	Diesel Oxidation Catalyst	Diesel Oxidation Catalyst	Diesel Oxidation Catalyst
Test Cycle	WMATA Cycle	WMATA Cycle	AVL 8-Mode
Reference Fuel	ULSD1	ULSD1	ULSD1
S-2% Reduction in Particulate	35	35	42
S-2% Reduction in Oxides of Nitrogen	28	16	19

Table 3. Summarized Emission Reduction Percentages in Particulate Matter and Oxides of Nitrogen attributable to switching to Syntroleum S-2 F-T fuel from conventional Ultra-Low Sulfur No. 1 Diesel Fuel (ULSD1) in Back-to-Back Tests

The third column of results in Table 3 is for a Caterpillar C-7 engine run on a laboratory dynamometer using the AVL 8-Mode emission measurement cycle. As described in more detail in Appendix A, the AVL 8-Mode test is an eight-mode steady-state engine test procedure designed to correlate with exhaust emission results of the U.S. Federal Test Procedure (FTP) Heavy-Duty Transient Cycle. (Woodward, et. al. 2006). Data from other testing (i.e. not back-to-back), while not as definitive, provides additional support for the data in Table 3. This additional data is discussed in Appendix A.

Emissions Summary
Table 3 shows that F-T diesel fuel can reduce particulate and NOx tailpipe emissions significantly even compared to the lowest-emission conventional diesel fuel available. Immediate emission reductions in the range 35% to 40% for particulates and 16% to 28% for NOx are achievable without any modifications to transit-system vehicles, equipment, or procedures.

D. Fuel Cell Analysis

The objective of this portion of the project was to research the utilization of F-T fuels for hydrogen production in association with future transit fleet applications of reformer/fuel-cell power systems. The thought process underlying this approach can be expressed by the following series of bullet points:

- The worldwide automotive industry is aggressively working on the many technical challenges associated with developing fuel cell power systems suitable for mass-production and for installation in a future generation of light-duty vehicles (LDVs) that can be technically and economically competitive in the LDV marketplace.
- It is unknown how long it will take to accomplish the foregoing, but it should then be quite practical to adapt these relatively small, mass-produced, cheap, and reliable LDV fuel cell systems to transit applications.
- The anticipated benefits of fuel cells, such as high efficiency and virtually zero emissions, are so important in transit applications that they should be deployed as soon as possible.
- Some method(s) or system(s) must also be developed for providing the hydrogen fuel that these fuel cells will require. Transit systems will not necessarily have the kind of tailor-made supporting infrastructure that original equipment manufacturers (OEM) will develop their LDV fuel cell systems to be compatible with.
- On-board reforming of liquid hydrocarbon fuels to produce hydrogen would maintain familiar transit-system fueling infrastructure.
- F-T fuels have virtually zero levels of sulfur, aromatics, and metals, making them considerably less difficult to reform, and far less detrimental to the long-term durability of reformer hardware, than conventional petroleum-derived liquid fuels.
- Reformation of F-T fuels is thus a potential enabler for the early deployment of fuel cells in transit applications.

State of the Industry
The fuel cell industry has undergone many changes since this project's inception in 2004. Many automotive OEM fuel cell development programs have recently focused on carrying compressed hydrogen rather than on-board reforming, and DOE has decided to stop supporting on-board reformation research for vehicular fuel cell applications. These trends are in large part attributable to the difficulties and hardware-durability issues associated with reforming conventional petroleum-derived liquid fuels, the only kind of liquid hydrocarbon fuels that are likely to be available in the marketplace large quantities over at least the next decade.

DOE's decision definitely had a negative effect on the type of projects that typically require federal funding, such as those run by small companies and academic institutions, and may have discouraged potential industry research somewhat as well. However, the utilization of F-T fuels for on-board hydrogen production as an interim solution to more quickly obtain the advantages of applications for reformer/fuel-cell power systems is still a technically viable approach. This approach is even economically viable when considering the extremely high costs that will be inherently associated with obtaining such "zero-emission" fuel cell power systems for at least a decade into the future.

On-Board Reforming

To utilize the energy content of hydrogen in fossil fuels, the hydrogen must be unlocked from the fuel molecules. This process is known as fuel "reforming." The major decision for industry is whether to 1) use hydrogen directly as a compressed gas or liquid stored on-board the vehicle, or 2) use a hydrogen-rich liquid fuel and dissociate the hydrogen from the parent molecule for use in the fuel cell via on-board reforming.

In high-temperature fuel cell systems (such as solid oxide), some fuels can be internally reformed. In relatively low-temperature fuel cell systems such as the proton exchange membrane (PEM) fuel cell, which is the predominant type of fuel cell being developed for transportation applications, the use of an external fuel processor before the fuel cell is necessary.

Although direct hydrogen fueling and on-board storage in vehicles is the option that most agree will be the long-term choice for both passenger and transit fuel cell powered vehicles, the reformation of hydrocarbon fuels using on-board reforming technology is a potential near-term source of hydrogen for transportation applications (Northeast Advanced Vehicle Consortium, 2000). Practical and cost-effective, on-board reforming of hydrocarbon fuels could provide benefits as an interim solution while long-term production and distribution systems for hydrogen are deployed. The benefits of on-board reforming are:

- Potentially allows use of existing fueling infrastructure,
- Offers minimal passenger acceptance impact,
- Affords inexpensive fuel delivery using proven technology, and
- Safety and handling risks and procedures are established for candidate fuels.

Drawbacks of reforming compared to direct hydrogen use include:

- Loss of efficiency,
- Added complexity, and
- Additional vehicle emissions.

Although most large automakers have focused recent efforts on on-board storage of compressed hydrogen to directly supply fuel cells, work is still being done on on-board reforming systems. For example, Renault and Nuvera Fuel Cells are currently pursuing development of an on-board reforming system that is capable of using F-T liquid fuel as a feedstock for Nuvera's 70-kW PEM fuel cell.

Further research of potential operation and cost impacts is needed in order to determine the ideal applications for utilizing F-T fuels in on-boarding reforming. The potential for increased emissions produced by reforming F-T fuel (compared to using compressed or liquefied hydrogen directly) must also be taken into consideration. However, the advantages of F-T fuel are clear: 1) existing infrastructure can be used with few changes to accommodate F-T diesel fuel, unlike compressed or liquefied hydrogen; and 2) on-board F-T diesel reforming poses very little safety, environmental, or associated liability risk for transit operators.

Transit Buses

Transit buses are especially good vectors for the introduction (or market maturation) of fuel cells because they are: 1) centrally fueled, 2) professionally maintained, 3) operated by central management, 4) operated in a fixed service area, and 5) have capital costs that are subsidized with public funds. (Chandler, 2006).

When this project was created, it was assumed that bus operators, being publicly funded, would be able to drive fuel cell advancements because they have access to public-benefit funds that could be applied to fuel cell demonstrations. It is now clear that automotive applications will likely drive future research, as that market is seen to be the only one large enough and having sufficient potential production volume to spur significant investments by industry. However, transit buses will still benefit from advances in PEM fuel cells being pursued by automotive manufacturers.

On-board reforming of F-T diesel may be an attractive interim solution to long-term alternatives for diesel-powered transit buses. Generally, the development of F-T diesel for on-board reforming could serve as an interim step before practical and widespread hydrogen availability is supported (i.e. before on-site electrolysis can be deployed at fueling stations). F-T diesel could serve as a convenient hydrogen carrier, produced at the source of natural gas or other feedstock, transported by truck, rail, or pipeline, and dispensed at local fueling stations.

DOE Decision Regarding On-Board Reforming

DOE has funded research and development (R&D) of on-board fuel processing for over ten years. This research focused on fuel-flexible fuel processing of hydrocarbons (gasoline, ethanol, methanol, and natural gas) for fuel cell vehicles. DOE convened two review panels to assess whether on-board reforming was a likely to meet a commercialization target of 2015 for fuel cell vehicles, and provide a "go/no-go" decision recommendation to DOE by June 2004.

An Independent Review Panel convened by DOE's National Renewable Energy Laboratory (NREL) for DOE's Hydrogen Program determined that no technology reviewed to date has been able to meet all of the 2004 decision criteria established by DOE, and saw no clear path for reaching all the ultimate criteria simultaneously within the established timeframe. The panel subsequently recommended a no-go decision on continued funding of on-board reforming research by DOE, although the panel made a number of recommendations for continued DOE funding of "fundamental" fuel processing work. A "Go/No-Go Decision Team" convened by DOE concurred with the panel's recommendation.

The major factors weighed in this decision were:
- The emergence of hybrid technologies has "obviated" the need for on-board reforming as a "bridge" technology towards the hydrogen economy.
- President Bush's announcement of a 2015 goal for commercialization decisions for hydrogen-powered vehicles has made development of a hydrogen fueling infrastructure more urgent, further reducing the need for on-board reforming.
- Pathways towards technical breakthroughs that would meet DOE's targets for cost, startup time, startup energy, and transient response could not be envisioned and prospects for overcoming these barriers were deemed low.

Although this decision will affect federally-supported development of on-board reforming, industry research continues. The use of on-board refueling, with extremely high quality, no-sulfur F-T fuels, will present real world, economically feasible options for the near term, while awaiting the arrival of the pure hydrogen economy.

Auxiliary Power Units: Interim Transit Bus Fuel Cell Application
While the automotive industry races to solve the problems associated with the use of fuel cells for automotive propulsion, and simultaneously drive the manufacturing costs down to affordable commercial levels, other nearer term applications for fuel cells have emerged with significant potential for transit bus application. An auxiliary power fuel cell system could provide power for transit bus auxiliary systems in place of mechanically-driven auxiliary systems.

One study performed for the U.S. Army's Tank-Automotive Research, Development and Engineering Command (TARDEC) demonstrated a significant fuel savings over mechanically-driven auxiliary systems in a class 8 on-highway tractor. The demonstration used a 20-kW fuel cell auxiliary power unit (APU) to provide air conditioning, water cooling pump, and compressed air systems via a 42-volt electrical system, and showed significant fuel savings over mechanically-driven auxiliary systems. Over the course of a 3,952-kilometer (2,470-mile) cross-country trip, the fuel cell APU reduced fuel consumption by an estimated 416 liters (110 gallons) of diesel fuel. (Redfield, et. al. 2006).

Fuel Cell Analysis Conclusion
While it appears that most manufacturers are now focusing on-board storage of compressed hydrogen rather than on-board reformation, there is still a place in the industry for on-board reforming in transit bus applications as an interim solution while the world awaits the development of a true hydrogen economy. F-T diesel, with zero-sulfur, low/zero aromatics, and the ability to be distributed by conventional national fuel distribution systems, is the enabling fuel that can make on-board reforming a viable interim step to the higher risk, longer term, pure hydrogen economy. The potential use of F-T diesel fuel may trigger manufacturers and government to reconsider and reassess the feasibility of on-board reformation for future fuel-cell powered transit bus application.

CONCLUSIONS

This project showed that F-T fuel can be stored, dispensed, and successfully run in transit buses at extremely low temperatures, without any modification to the bus engines. Also, F-T biodegrades faster than conventional diesel fuels, which reduces potential environmental damage in the event of a spill or leak.

F-T fuel has many advantages: it reduces tailpipe diesel exhaust emissions when compared to conventional diesel fuels; it can be easily integrated with existing fuel infrastructure; and it can be produced from domestically available feedstocks, potentially reducing U.S. dependence on imported oil. However, F-T has a major barrier—cost. F-T feedstocks may be domestically available, but their cost makes the fuel economically prohibitive at this time. Until either global petroleum prices rise to a level comparable to F-T fuels, or F-T technology develops to the point that F-T can be cost competitive with petroleum-based fuels, a large-scale F-T industry remains out of reach. However, projects such as this one provide valuable information that can help the U.S. transportation and energy industries to move one step closer toward widespread F-T fuel use.

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APPENDICES

Appendix A:
Requisites for Measuring Effects on Emissions of Changes in Fuel Properties

Making meaningful measurements of an effect on engine emissions as small as that attributable to the influence of fuel properties requires, at a minimum:

1. The ability to monitor and precisely control engine conditions to obtain test-to-test operational consistency;
2. Exhaust sampling equipment and procedures that have been demonstrated to preclude sample contamination (notably from atmospheric air, which may otherwise be present in differing amounts from test-to test);
3. Technically sophisticated analytical methods and instruments (with demonstrated high sensitivity to the concentration range of interest for the chemical species to be measured and with virtually no interference from other chemical species that may, or may not, be present);
4. In-use instrument and overall-system calibration, verified frequently by using both "zero" and "span" reference gases;
5. Simultaneous measurement of all relevant emissions, especially inclusion of particulates along with NOx gaseous emissions, since these two are known to "trade-off" in diesel combustion;
6. Back-to-back testing to eliminate variables associated with different engines and vehicles.

Appendix B:
Additional Emissions Data

Relative weights of particular modes are represented by the area of bubbles in Figure 8.
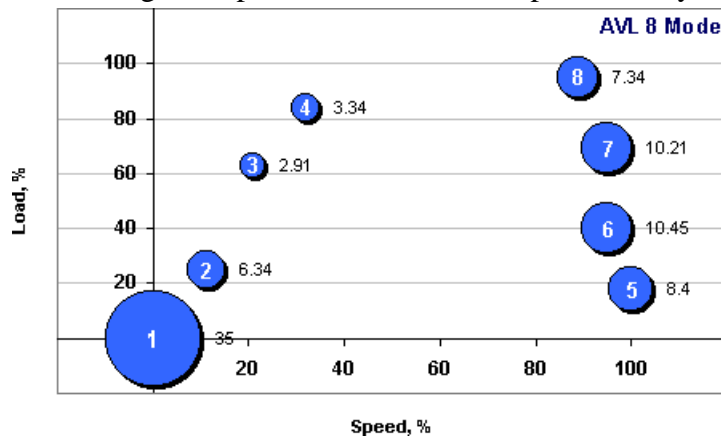
Figure 8. AVL 8-Mode Emission Test-Cycle Visual Weight Factors

Other (Not Back-to-Back) Emission Data for F-T and Conventional Fuels

Figure 9 shows NOx emissions for the six buses, numbered 531 through 534, 536, and 537A, along with the fuel they were tested on, Syntro (Syntroleum) or Jet-A. The results are quite consistent within each group of three buses running on each fuel. This consistency tends to support the implicit assumption that the bus-to-bus variation is relatively small. On this basis, the apparent increase in NOx emissions with F-T fuel is approximately 23%. This is in contrast to the results in Table 3 of the Emissions section of this report, which show reductions of approximately 20% in NOx emissions with F-T fuel.
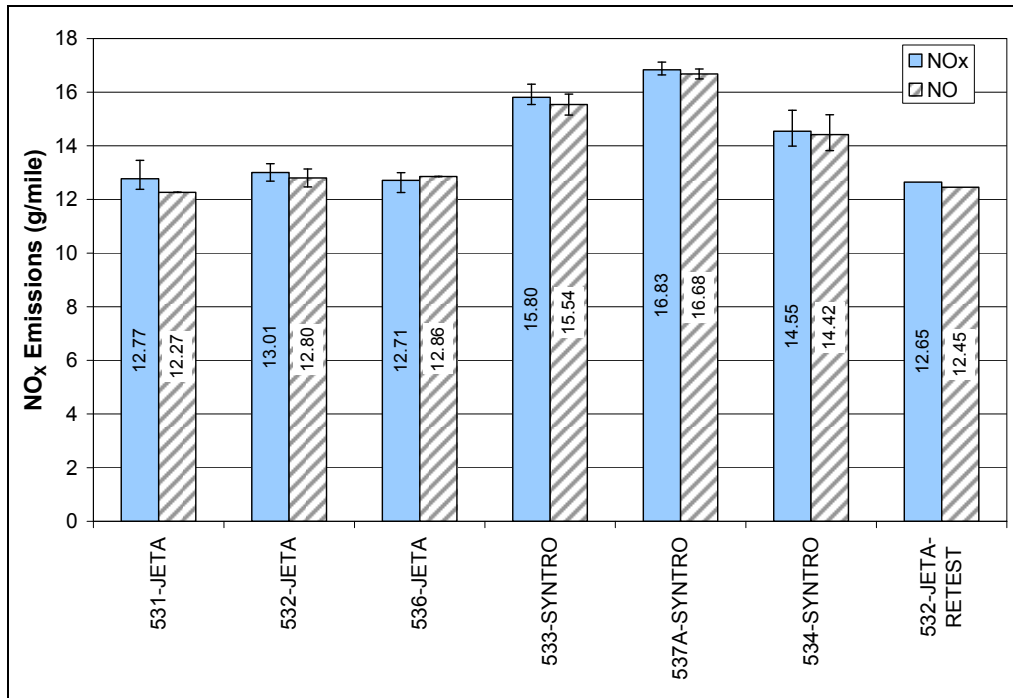
Figure 9. Oxides of Nitrogen (NOx and NO) Emissions from six Denali National Park buses (with bus-numbers shown) operating on conventional Jet-A (which is used as No. 1 diesel fuel in Alaska), and on Syntroleum S-2 F-T diesel fuel

As an initial attempt to understand this discrepancy in the direction of the change in NOx emissions with F-T fuel, bus 532 was retested. Results were very similar to the initial test on bus 532, indicating that emission-measurement instrument "drift" was unlikely to be the cause of the unexpected results.

Figure 10 shows particulate matter emissions for the same series of tests on the six Denali buses. The apparent decrease in particulate emissions with F-T fuel was approximately 25%. This is somewhat less than the values indicated in Table 3 for particulate emissions, but at least it is in the same direction.

Figure 10. Particulate Matter (PM) Emissions from six Denali National Park buses (with bus-numbers shown) operating on conventional Jet-A (which is used as No. 1 diesel fuel in Alaska), and on Syntroleum S-2 F-T diesel fuel

Follow-up investigation, including the dynamometer-based emission tests summarized in Table 3, revealed several interesting facts about the 2004 model-year Caterpillar C-7 engine. Although not publicly admitted by Caterpillar, this engine uses a homogeneous-charge compression-ignition (HCCI) strategy under some low-load conditions. This strategy can be effective for reducing both diesel particulate and NOx emissions, but it is difficult to control and its use is limited to the low-load regime with current technology.

The tables in Part C of the Appendix show the complete set of dynamometer-based emission data for the Caterpillar C-7 engine; three runs on each of three fuels at all eight of the conditions shown in Figure 8. At the lowest load conditions, Modes 1 and 2 in Figure 8, this data-set shows high run-to-run variability in NOx, with correspondingly high, but opposite-direction variability, in both CO and hydrocarbon emissions. This is exactly the type of variability that would be expected for an engine control system that is "hunting" for opportunities to apply HCCI-type operation.

In retrospect, the choice of the WMATA operating cycle for the Denali National Park bus emission testing (for the sake of consistency), was a poor choice. The WMATA cycle is indeed representative of congested urban-traffic transit-bus operation, with a significant percentage of relatively low-speed and low-load operation. However, the Denali National Park buses, which must climb steep grades on rough roads, actually operate under much heavier average loads than urban buses. Furthermore, the relatively low-load WMATA cycle chosen for emission testing apparently provided multiple "opportunities" for the Caterpillar C-7 engines in the Denali buses to run in HCCI-type operation.

The problem for F-T fuels with HCCI-type technology is that to achieve minimum emissions, the engine control system must be calibrated for the Cetane Number range of the fuels that the engine will be using. Typical conventional diesel fuels in the U.S. have Cetane Numbers in the range of 40 to 45. However, hydrogen-saturated F-T diesel fuel has a much higher (literally "off the chart") Cetane Number of at least 70.

In HCCI operation, the fuel is injected "early and often" in an attempt to obtain a lean, but nearly homogeneous, charge of fuel-air mixture which will then autoignite, ideally producing low emissions of NOx and particulate, but relatively high emissions of CO and hydrocarbons. Exhaust aftertreatment technology, including the diesel oxidation catalyst, but especially the diesel particulate filter, can subsequently "clean-up" the CO and hydrocarbon emissions.

Extremely high Cetane-Number F-T fuel ignites much earlier than conventional diesel fuel in HCCI-type operation. Presumably, the HCCI engine's control system could have been calibrated to take advantage of F-T fuel's inherent lower emission characteristics, rather than inadvertently causing an increase in NOx emissions with F-T fuel. The early ignition caused by F-T fuel's high Cetane Number in HCCI-type operation (when not calibrated for high-Cetane fuel) has the same net effect on increasing NOx emissions as advancing the fuel-injection timing in a more traditional diesel engine.

In an emission measurement program with an identical design to that used for the Denali National Park buses just described (i.e. not using back-to-back testing), emissions were measured from six WMATA buses, three using Syntroleum S-2 F-T fuel, and three using ULSD1. However, these WMATA buses were much older (with "traditional" diesel technology), had been in transit-service operation for over four years and had all accumulated between 180,000 and 220,000 odometer miles, far more than the new Denali buses at the time they were tested.

Nonetheless, NOx emissions for these older WMATA buses, as shown in Figure 9, were remarkably consistent within the two fuel-groups, with an apparent reduction of 22% in NOx attributable to S-2 fuel, which is well in-line with the summarized back-to-back NOx reduction values in Table 3. For particulate emissions, however, as shown in Figure 10, bus-to-bus variations for these high-mileage buses were very large, obscuring any fuel-effect. This is the reason that in subsequent emission testing at WMATA, as summarized in Table 3, the back-to-back testing approach was used; the same three buses were tested back-to-back on the two fuels to be compared.

Figure 11. Oxides of Nitrogen (NOx and NO) Emissions from six WMATA buses (with bus-numbers shown) operating on conventional ULSD1, and on Syntroleum S-2 F-T diesel fuel
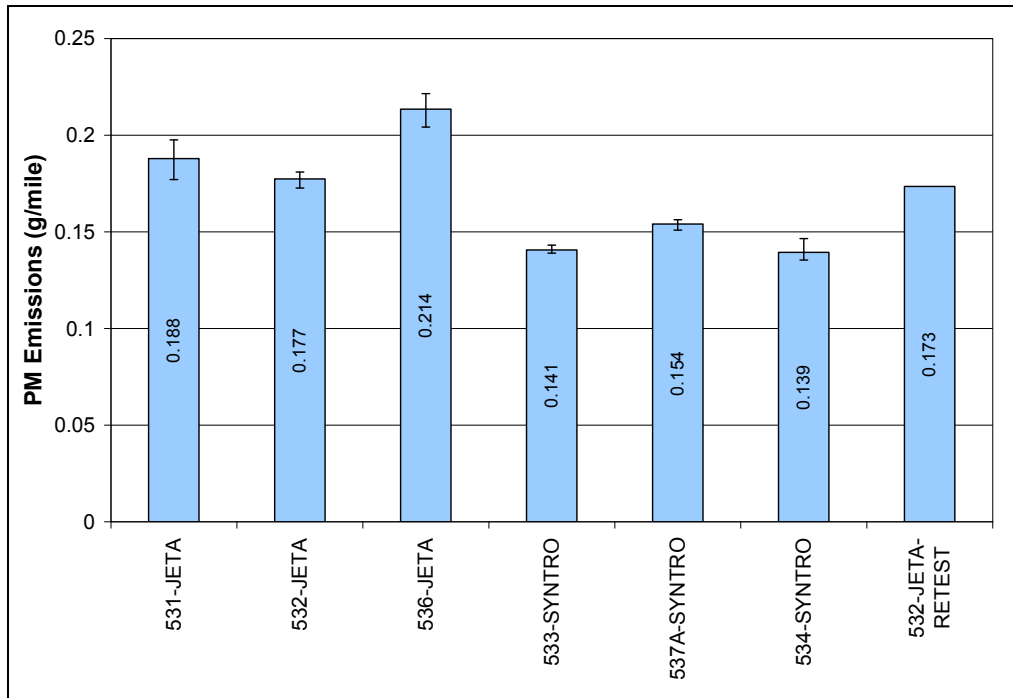

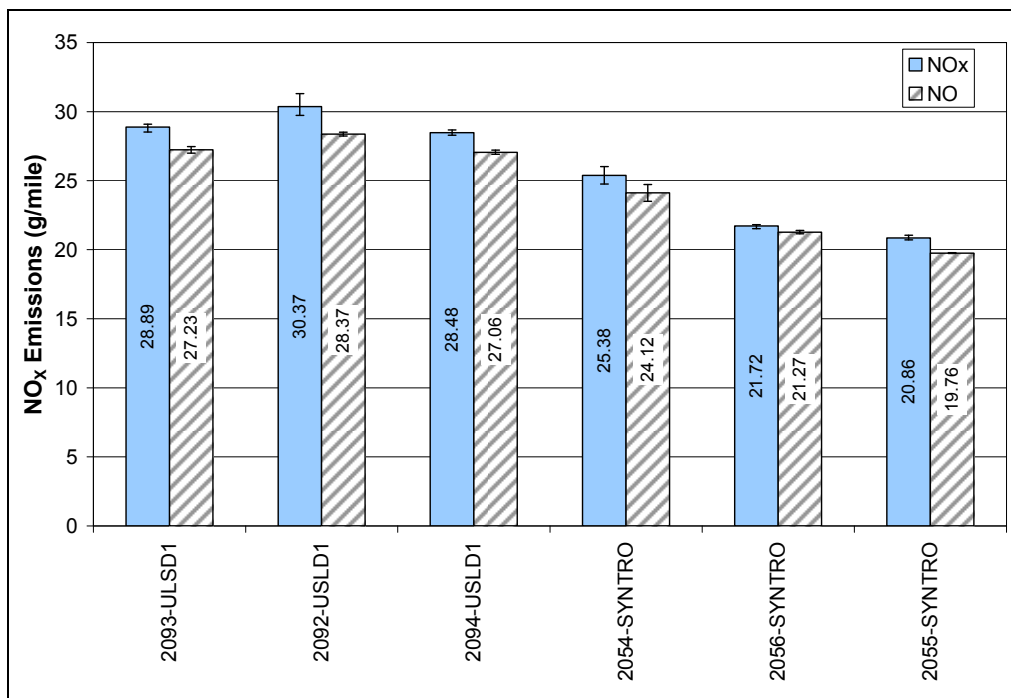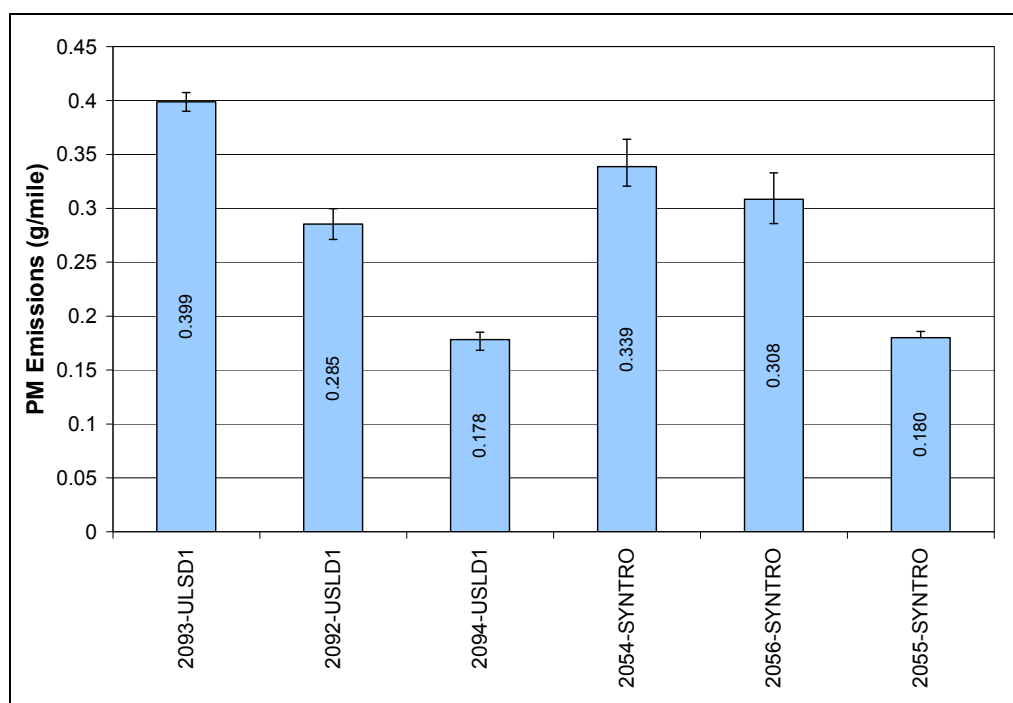**Figure 12. Particulate Matter (PM) Emissions from six WMATA buses (with bus-numbers shown) operating on conventional ULSD1, and on Syntroleum S-2 F-T diesel fuel**

Appendix C:
Emission data from dynamometer-based back-to-back testing of the Caterpillar C-7 engine; three runs on each of three different fuels using the AVL 8-Mode cycle.

AVL 8 Mode: Average Weighted Brake Specific Emissions

		Rated	Rated		
Engine: CAT C7 2004	Speed: 2400	Power: 230 HP	Disp. (L) 7.2	Fuel Type Syntroleum	

PUMA File 5758_synt_19Apr05   2319
SPC File 1012

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	PM
1	35	799	-5.08	-0.43	45.69	3857	14.68	10.68	-0.15	15.99	1350	5.14	3.74	
2	6.34	887	138.67	12.88	90.96	11651	36.28	13.58	0.82	5.77	739	2.30	0.86	
3	2.91	1057	407.28	45.08	212.46	32936	156.72	19.52	1.31	6.18	958	4.56	0.57	
4	3.34	1244	614.46	80.05	307.23	59771	176.26	27.46	2.67	10.26	1996	5.89	0.92	
5	8.4	2399.6	94.79	23.82	111.67	36998	96.14	73.54	2.00	9.38	3108	8.08	6.18	
6	10.45	2315	234.08	56.75	181.94	56862	109.51	76.47	5.93	19.01	5942	11.44	7.99	
7	10.21	2315	402.43	97.56	250.3	85128	1122.7	98.76	9.96	25.56	8692	114.63	10.08	
8	7.34	2213.1	587.04	136.05	474.75	102940	848.88	76.87	9.99	34.85	7556	62.31	5.64	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									32.53	127.00	30341	214.34	35.98	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→										3.90	933	6.59	1.11	0.030

PUMA File 5776_synt_19Apr05   2322
SPC File 1013

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	PM
1	35	800.1	-6.63	-0.56	23.6	3861	329.34	30.67	-0.20	8.26	1351	115.27	10.73	
2	6.34	887	138.49	12.86	75.27	11649	213.61	22.24	0.82	4.77	739	13.54	1.41	
3	2.91	1057	408.31	45.19	214.78	33157	145.07	17.75	1.32	6.25	965	4.22	0.52	
4	3.34	1244	612.92	79.85	313.92	59655	167.19	24.05	2.67	10.48	1992	5.58	0.80	
5	8.4	2400.2	100.17	25.18	113.78	37027	96.52	72.84	2.12	9.56	3110	8.11	6.12	
6	10.45	2315	232.76	56.43	183.01	56133	108.11	76.06	5.90	19.12	5866	11.30	7.95	
7	10.21	2314.9	402.12	97.48	255.04	85166	1119.6	95.81	9.95	26.04	8695	114.31	9.78	
8	7.34	2213	586.74	135.98	466.52	102416	849.89	77.42	9.98	34.24	7517	62.38	5.68	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									32.55	118.73	30236	334.72	43.00	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→										3.65	929	10.28	1.32	0.030

PUMA File 5780_synt_19Apr05   2328
SPC File 1014

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	PM
1	35	800	-0.79	-0.07	22.21	3619	370.26	32.55	-0.02	7.77	1267	129.59	11.39	
2	6.34	887	138.07	12.82	66.3	11687	226.9	23.4	0.81	4.20	741	14.39	1.48	
3	2.91	1057	405.54	44.89	199.48	33035	153.75	19.38	1.31	5.80	961	4.47	0.56	
4	3.34	1244	613.8	79.96	293.75	59954	179.97	27.68	2.67	9.81	2002	6.01	0.92	
5	8.4	2399.7	95.56	24.01	107.3	37256	101.29	74.33	2.02	9.01	3130	8.51	6.24	
6	10.45	2314.9	232.29	56.31	171.09	56223	110.39	76.35	5.88	17.88	5875	11.54	7.98	
7	10.21	2315.1	402.45	97.57	245.63	84632	1161.91	97.8	9.96	25.08	8641	118.63	9.99	
8	7.34	2213	586.65	135.95	449.18	103196	872.24	81	9.98	32.97	7575	64.02	5.95	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									32.61	112.53	30192	357.16	44.52	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→										3.45	926	10.95	1.37	0.030

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→→   3.67   929   9.28   1.26   0.030

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: CAT C7 2004	Rated Speed: 2400	Rated Power: 230 HP	Disp. (L) 7.2	Fuel Type WMATA

PUMA File 5703_WMATA_1_28Apr05 2383
SPC File 1019

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	PM
1	35	800.6	3.55	0.3	36.36	3527	584.03	81.59	0.11	12.73	1235	204.41	28.56	
2	6.34	887	155.12	14.41	80.55	12472	342.53	38.63	0.91	5.11	791	21.72	2.45	
3	2.91	1057	445.89	49.35	251.62	36239	193.49	30.63	1.44	7.32	1055	5.63	0.89	
4	3.34	1244	714.92	93.13	393.53	69780	240.17	43.23	3.11	13.14	2331	8.02	1.44	
5	8.4	2400.2	112.63	28.31	146.68	39229	173.09	136.01	2.38	12.32	3295	14.54	11.42	
6	10.45	2315	252.17	61.13	224.18	61229	150.3	118.03	6.39	23.43	6398	15.71	12.33	
7	10.21	2315	433.99	105.21	299.48	90564	1509.73	151.25	10.74	30.58	9247	154.14	15.44	
8	7.34	2213	637.01	147.63	564.12	111225	1099.32	109.94	10.84	41.41	8164	80.69	8.07	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									35.91	146.03	32515	504.86	80.61	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										4.07	905	14.06	2.24	0.057

PUMA File 5704_WMATA_2_28Apr05 2385
SPC File 1020

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	PM
1	35	699.5	0.56	0.04	85.77	3360	40.07	15.45	0.01	30.02	1176	14.02	5.41	
2	6.34	887	156.21	14.51	179.21	12696	193.24	29.47	0.92	11.36	805	12.25	1.87	
3	2.91	1057	447.84	49.57	258.51	36157	184.39	26.95	1.44	7.52	1052	5.37	0.78	
4	3.34	1244.1	716.03	93.29	408.52	68856	238.94	39.34	3.12	13.64	2300	7.98	1.31	
5	8.4	2400.3	112.55	28.29	145.76	39917	166.87	136.27	2.38	12.24	3353	14.02	11.45	
6	10.45	2314.9	252.71	61.26	223.48	61505	142.46	118.95	6.40	23.35	6427	14.89	12.43	
7	10.21	2314.9	435.43	105.56	305.12	90995	1484.9	149.64	10.78	31.15	9291	151.61	15.28	
8	7.34	2213	638.02	147.86	567.31	111296	1094.62	113.71	10.85	41.64	8169	80.35	8.35	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									35.90	170.94	32573	300.48	56.88	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										4.76	907	8.37	1.58	0.045

PUMA File 5777_WMATA_4_29Apr05 2390
SPC File 1022

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	PM
1	35	801.1	2.31	0.19	91.54	4255	71.67	20.27	0.07	32.04	1489	25.08	7.09	
2	6.34	887	156.06	14.5	222.71	13120	37.44	18.25	0.92	14.12	832	2.37	1.16	
3	2.91	1057	446.46	49.42	251.13	36193	203.77	25.01	1.44	7.31	1053	5.93	0.73	
4	3.34	1244.1	718.03	93.55	404.77	69441	251.7	36	3.12	13.52	2319	8.41	1.20	
5	8.4	2399.8	108.61	27.3	141.59	39701	167.54	141.01	2.29	11.89	3335	14.07	11.84	
6	10.45	2315	252.38	61.18	216.67	60853	144.67	122.86	6.39	22.64	6359	15.12	12.84	
7	10.21	2315	435.14	105.49	293.97	90806	1561.61	156.39	10.77	30.01	9271	159.44	15.97	
8	7.34	2213.1	638.19	147.9	551.96	111549	1120.03	116.08	10.86	40.51	8188	82.21	8.52	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									35.86	172.05	32847	312.64	59.35	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										4.80	916	8.72	1.66	0.053

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→− 4.54   910   10.38   1.83   0.052

AVL 8 Mode: Average Weighted Brake Specific Emissions

		Rated		Rated										
Engine: CAT C7 2004		**Speed:** 2400		**Power:** 230 HP		**Disp. (L)** 7.2			**Fuel Type** Denali					

PUMA File 5781_Denali_21Apr05 2343
SPC File 2343

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	g/kw-hr
1	35	799.7	7.17	0.6	34.36	3310	528.08	76.23	0.21	12.03	1158	184.83	26.68	
2	6.34	887	156.02	14.49	83.51	12570	322.69	34.95	0.92	5.29	797	20.46	2.22	
3	2.91	1057	427.24	47.29	251.2	35532	194.03	28.16	1.38	7.31	1034	5.65	0.82	
4	3.34	1244	628.55	81.88	369.42	63054	225.74	41.06	2.73	12.34	2106	7.54	1.37	
5	8.4	2399.7	100.69	25.3	143.05	39587	169.8	145.64	2.13	12.02	3325	14.26	12.23	
6	10.45	2215	239.1	55.46	200.09	55202	146.38	119.5	5.80	20.91	5769	15.30	12.49	
7	10.21	2215	410.1	95.13	274.02	83096	1346.6	147.32	9.71	27.98	8484	137.49	15.04	
8	7.34	2212.9	600.02	139.05	555.74	108281	1003.91	115.91	10.21	40.79	7948	73.69	8.51	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									33.08	138.66	30621	459.21	79.36	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**4.19**	**926**	**13.88**	**2.40**	**0.059**

PUMA File 5774_Denali_22Apr05 2349
SPC File 2349

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	g/kw-hr
1	35	799.7	5.9	0.49	96.1	3828	37.2	16.92	0.17	33.64	1340	13.02	5.92	
2	6.34	887	157.13	14.6	184.65	12840	187.79	24.52	0.93	11.71	814	11.91	1.55	
3	2.91	1057	428.38	47.42	251.8	35489	178.23	24.5	1.38	7.33	1033	5.19	0.71	
4	3.34	1244	626.03	81.55	362.78	63147	217.94	35.81	2.72	12.12	2109	7.28	1.20	
5	8.4	2399.6	97.46	24.49	139.34	38469	180.81	154.07	2.06	11.70	3231	15.19	12.94	
6	10.45	2315	238.15	57.73	213.31	59454	149.34	123.59	6.03	22.29	6213	15.61	12.92	
7	10.21	2315	411.01	99.64	305.32	89354	1355.52	145.31	10.17	31.17	9123	138.40	14.84	
8	7.34	2213.1	600.09	139.07	546.04	108001	1023.5	111.28	10.21	40.08	7927	75.12	8.17	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									33.67	170.03	31790	281.71	58.25	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**5.05**	**944**	**8.37**	**1.73**	**0.051**

PUMA File 5701_Denali_22Apr05 2353
SPC File 2353

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	g/kw-hr
1	35	800.1	3.23	0.27	90.25	3942	51.58	18.24	0.09	31.59	1380	18.05	6.38	
2	6.34	887	158.22	14.7	198.6	13215	37.17	16.34	0.93	12.59	838	2.36	1.04	
3	2.91	1057	430.48	47.65	251.06	35858	192.66	24.5	1.39	7.31	1043	5.61	0.71	
4	3.34	1244	627.46	81.74	358.96	63384	221.43	35.84	2.73	11.99	2117	7.40	1.20	
5	8.4	2400.1	103.55	26.03	139.19	39523	180.5	150.34	2.19	11.69	3320	15.16	12.63	
6	10.45	2314.9	238.4	57.79	209.82	60245	150.68	123.81	6.04	21.93	6296	15.75	12.94	
7	10.21	2314.9	411.28	99.7	288.44	89273	1348.39	145.29	10.18	29.45	9115	137.67	14.83	
8	7.34	2213.1	600.76	139.23	555.21	108832	999.84	111.03	10.22	40.75	7988	73.39	8.15	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									33.77	167.29	32096	275.38	57.88	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**4.95**	**951**	**8.16**	**1.71**	**0.052**

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→→ **4.73** **940** **10.13** **1.95** **0.054**